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Alternate Source Evaluation for the Aircrew Integrated Helmet System Comanche Compatibility Program Phase IIB

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Two alternate image sources under consideration for the Comanche helmet-mounted display have been evaluated for image quality. These sources were developed under phase IIA of a contract monitored by the Program Manager, Aircrew Integrated Systems (PM-ACIS), Huntsville, Alabama. One source is a 24-micron electroluminescent (EL) display with 1280 x 1024 resolution, developed by Honeywell, Inc., Minneapolis, Minnesota, and Planar Systems, Inc., Beaverton, Oregon. The second source is a 12-micron liquid crystal display (LCD) also with 1280 x 1024 resolution, developed by Kaiser Electronics, San Jose, California, and Kopin Corporation, Tauton, Massachusetts.

Measurements of the following parameters were made for both image sources: pixel geometry, pixel defects, maximum luminance, luminance uniformity, contrast uniformity, Gamma, contrast transfer function, gray levels, and temporal response. Both types of image sources performed reasonably well. However, the EL display suffered from image "burn-in" and excess pixel defects. The LCD display generally performed better; however, a major component, the backlight, which is important in defining

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19. Abstract (continued):

maximum luminance and luminance uniformity, was not representative of the backlight to be used in the final design.

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Introduction

The Aircrew Integrated Helmet System (AIHS) Comanche compatibility program is supporting the RAH-66 Comanche Helmet Integrated Display and Sighting System (HIDSS) helmet-mounted display (HMD) program through the investigation of alternative HMD designs, to include the investigation of new technology image sources. The current Development and Validation Program (DVP) version of the HIDSS (Figure 1) uses two miniature (1-inch diameter) cathode ray tubes (CRTs) (Figure 2) as image sources.

Miniature CRTs have been used successfully in the monocular Integrated Helmet Display and Sighting System (IHADSS) in the AH-64 Apache. CRTs currently provide the best image quality available. However, CRTs, even miniature ones, present a number of undesirable characteristics. These include high weight and power consumption, heat generation, and, when helmet-mounted, center of mass offsets. But, more importantly, miniature CRT availability has declined to virtually nil. Miniature CRT demand is limited to military use, making their production financially unfeasible. This would significantly impact the fielding of the current HIDSS CRT design. For this reason, it was prudent to investigate alternate image sources.

Phase I of the alternate program resulted in two subcontractor alternative design proposals. At the end of phase IIA, each subcontractor submitted representative models of their proposed HIDSS design. While both designs showed promise, neither incorporated image sources which were sufficiently matured to fully meet the Comanche requirements (Gentex, 1998). For this reason, phase IIB was expanded to focus on image source enhancements.

Figure 1. CRT DVP design for Comanche HIDSS.

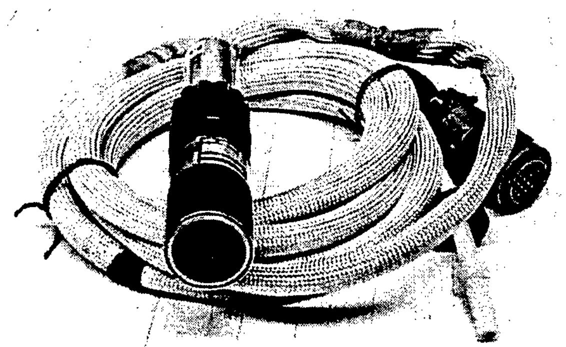


Figure 2. Miniature CRT.

The CRT-based DVP HIDSS design was evaluated by the U.S. Army Aeromedical Research Laboratory (USAARL) in the latter part of 1997 (Harding et al., 1998). This report documents the image quality performance of the miniature electroluminencent (EL) display image source (Figure 3) submitted by Honeywell, Inc., Minneapolis, MN, and the miniature liquid crystal display (LCD) image source (Figure 4) submitted by Kaiser Electronics, Inc., San Jose, CA.

Image sources

The Honeywell, Inc., EL image source is a nominal 24-micron (μm), 1280 X 1024 resolution display manufactured by Planar Systems, Inc., Beaverton, OR. The Kaiser Electronics LCD image source has the same 1280 X 1024 resolution, but is based on a nominal 12 micron pixel and is manufactured by Kopin Corporation, Tauton, MA. Honeywell, Inc., provided two test items, identified as #42 and #44. Kaiser Electronics provided two test items, identified as #1 and #39 and a "set up" display, used to validate the electronic configuration.

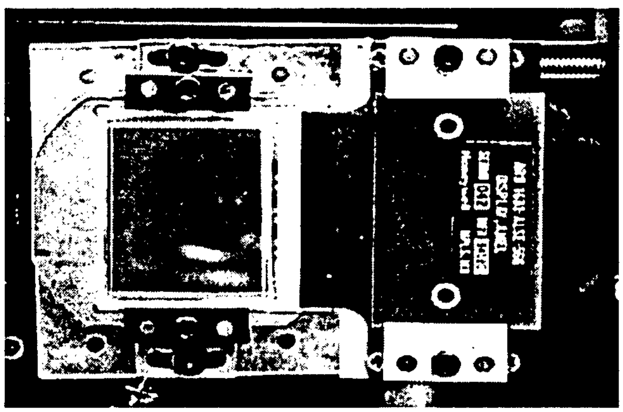


Figure 3. Honeywell, Inc., miniature 1280 X 1064 EL image source.

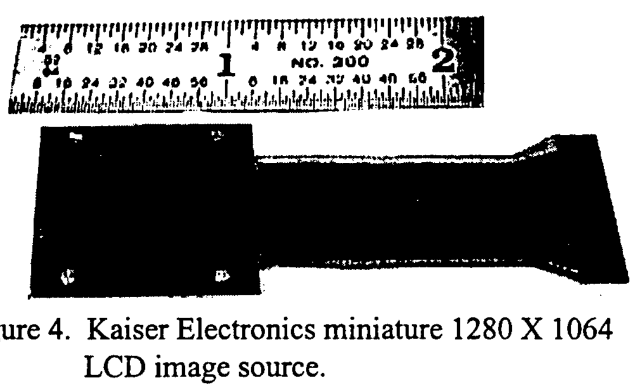


Figure 4. Kaiser Electronics miniature 1280 X 1064 LCD image source.

Honeywell, Inc. electroluminenecent (EL) display tests

The first EL source (#44) experienced a catastrophic failure during power up. All data reported here are based on test source #42, P/N 1680-ALSE-I-566. Honeywell, Inc., provided the required drive and control electronics for the evaluation. All testing was performed at USAARL. Some tests were observed by Honeywell, Inc., engineers.

Pixel geometry

Test Item ID: Honeywell, EL, 24-μm, Number 42.

Objective: To document pixel geometry and pixel pitch.

Equipment: A Zeiss, Inc. light microscope with a 16X and 50X objective lens; the microscope was equipped with a video camera [COHU Model # 768X493 charge coupled device (CCD)]; a laboratory computer with a video capture card and Adobe Photoshop software.

Procedure: Image source was placed on an XY-translator stage beneath a microscope objective. The panel was lighted from above via the microscope's light source. Using a 50X objective lens, a small patch of pixels was imaged by the CCD camera and digitally captured by computer, and the image was saved as a graphics file. Using Adobe Photoshop, the image was analyzed, and measurements of pixel geometry were made using a mensural technique. Calibration was calculated using a previously stored image of a 1/100mm microscope stage.

Results: Figure 5 is a photomicrograph of a pixel patch on the EL source of about 12 by 9 pixels. The photomicrograph provides details of the microscopic structure not commonly seen under normal viewing conditions. Figure 6 shows an enlarged section of the pixel patch shown in Figure 5. We measured pixel pitch to be 24.1 µm. The pixel fill factor was virtually impossible to measure owing to the Lambertian output distribution of light of the EL display. Planar engineers reported that the fill factor value was nominally 0.84.

Discussion: The difficulty of accurately measuring a fill factor for this source is the reflectance of emitted light from the areas surrounding the active pixel structure. Our attempts generally provided a measure that was greater than the pixel pitch. This leads to the concept of an "effective" fill factor which we discuss further in the predicted modulation transfer function (MTF) section.

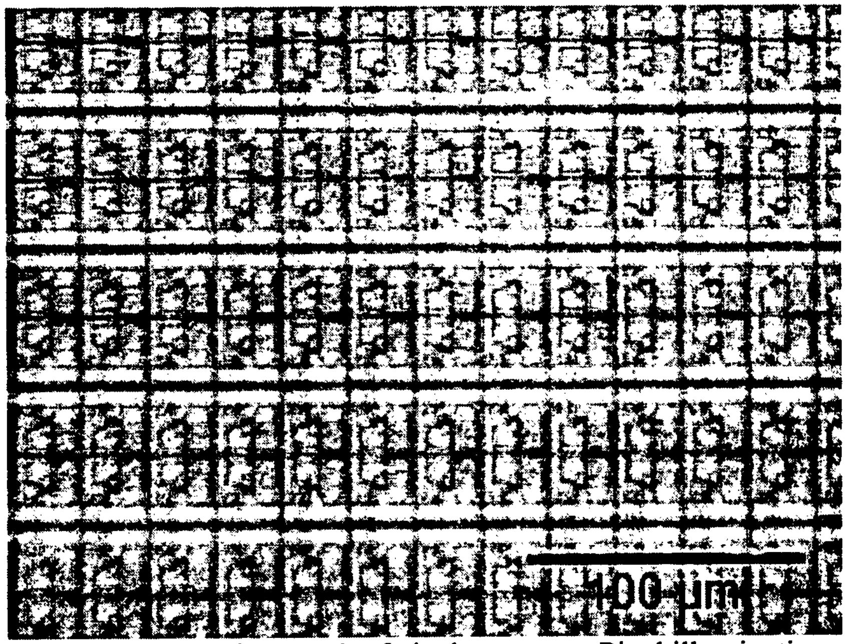


Figure 5. Photomicrograph of pixel structure. Pixel illumination is artificial and provided from above. Please note the calibration scale.

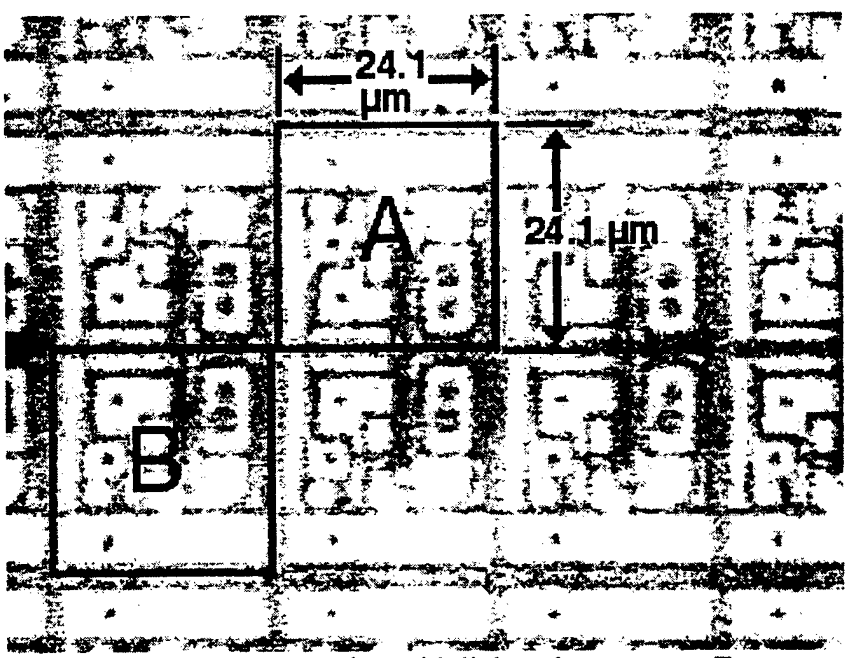


Figure 6. Enlarged subsection with light enhancement. Two pixels are highlighted (pixels A and B). Using computer mensuration, we measured pixel pitch to be 24.1 μm, which also equates to the pixel size.

Pixel defects

Source Sample: Honeywell, EL, 24-μm, Number 42.

Objective: To document display and pixel defects.

Equipment: A Zeiss, Inc. light microscope with a 16X and 50X objective lens; the microscope is equipped with a video camera (COHU Model # 768X493 CCD); a laboratory computer with a video capture card; Adobe Photoshop software.

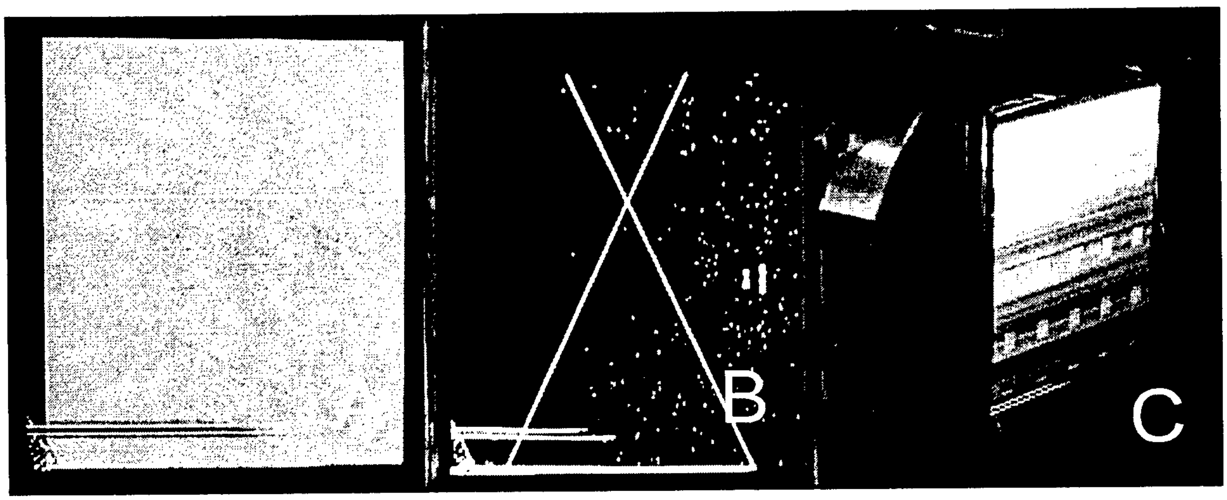


Figure 7. Photomicrographs of pixel defects.

Results: In Figure 7, photo A, note the two primary columns of pixels that are "stuck on" in the display's lower right quadrant (picture's lower left quadrant). Photo B shows a cross pattern, and all other pixels are off. Note the many pixels that are permanently on. In photo C, a gray scale pattern is shown. Note the bleed-through of small squares. The squares are part of a 25-square pattern previously displayed for measuring display uniformity. This "burn-in" of previously displayed patterns was a recurring problem.

Discussion: The frequency of pixel defects is high. While this is a concern, it must be remembered that the device under test is a prototype. Of greater concern is the "burn-in" problem which will significantly degrade performance.

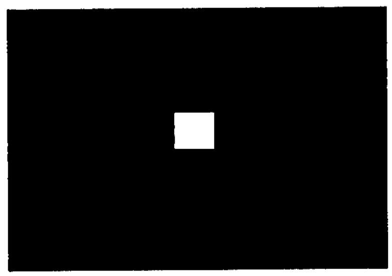
Maximum luminance

Source Sample: Honeywell, EL, 24-μm, Number 42.

Objective: To determine the maximum luminance.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 1-degree circular aperture.

Display pattern: A 100 by 100 pixel square centrally located and set to maximum luminance (digital level = 63). All other pixels were set to zero.



Procedure: The plane of the display was aligned with the photometer focal plane. The 100 pixel square target was centered with the center of the viewing photometer aperture. We measured calibrated luminance in footlamberts (fL). To investigate maximum contrast for this condition, luminance measurements were taken at points 100 pixels to the right and below the center of the 100 pixel square target.

Results: Maximum luminance was measured at 657.24 fL. Table 1 provides luminance and contrast values. Contrast ratio equals the maximum or target luminance divided by the minimum or background luminance (L_{max}/L_{min}).

Table 1.
EL luminance and contrast values.

	Luminance (fL)	Contrast ratios
Target	657.24	
Side	3.06	215
Below	2.01	327

Discussion: Honeywell estimates that the system transmittance of their HMD design will be between 30 and 60 percent. This transmittance would produce peak luminances of 197 to 394 fL.

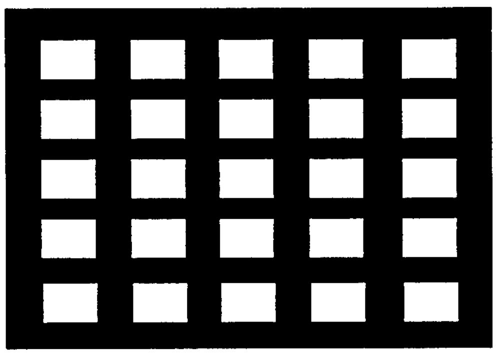
Luminance uniformity

Source Sample: Honeywell, EL, 24-μm, Number 42.

Objective: To determine variation in luminance for both on-axis and off-axis orientations.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 20-minute circular aperture.

Display pattern: The pattern consisted of 25 windows, each 80 horizontal by 64 vertical pixels. Each rectangular block of pixels was set to a maximum gray level of 63. The background was set to a gray level of 0.



Procedure: On-axis - Luminance measurements were taken for each of the 25 windows. Off-axis - Luminance measurements were taken for only the center window at each of several horizontal and vertical angles.

Results: On-axis luminance in footlamberts for each of the 25 windows is provided in Table 2.

Table 2.
EL on-axis luminance.

601.28	599.22	588.92	588.92	572.45
603.34	599.22	595.10	590.98	578.63
609.51	605.40	599.22	593.04	580.69
609.51	601.28	603.34	599.22	586.86
609.51	603.34	605.40	590.98	586.86

On-axis percent deviation from the average luminance is provided in Table 3.

Table 3.
EL on-axis percent deviation from the average luminance.

0.87%	0.53%	-1.20%	-1.20%	-3.97%
1.22%	0.53%	-0.17%	-0.86%	-2.93%
2.25%	1.56%	0.53%	-0.51%	-2.58%
2.25%	0.87%	1.22%	0.53%	-1.55%
2.25%	1.22%	1.56%	-0.86%	-1.55%

Off-axis normalized luminance for the center window as function of horizontal and vertical rotation is given in Table 4. These data are plotted in Figure 8.

Table 4.
EL off-axis normalized luminance.

Degrees of Rotation	Vertical Luminance	Horizontal Luminance
30	1.02	----
25	1.00	----
20	1.02	1.01
15	0.99	1.00
10	0.99	0.99
5	1.01	1.00
0	1.00	1.00
-5	1.01	1.00
-10	1.01	0.99
-15	0.97	1.00
-20	1.01	1.01
-25	1.00	----
-30	1.03	----

Note: Due to the prototype design, there were constraints on the horizontal measurements.

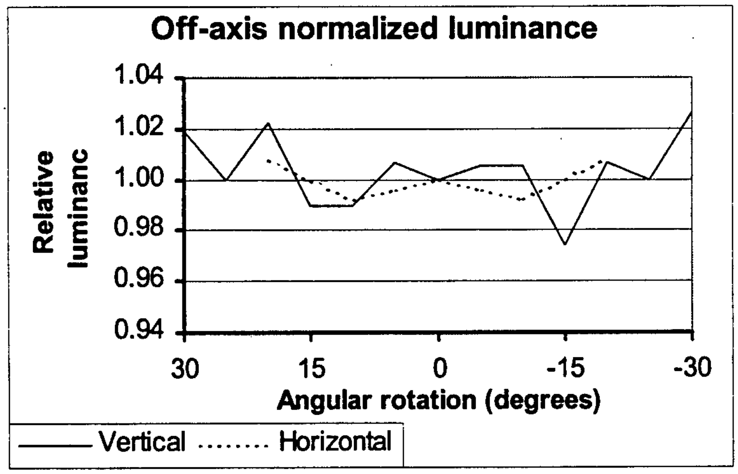


Figure 8. EL off-axis normalized luminance.

Discussion: Both the on-axis and off-axis deviations from the average were within the allowed ±20% deviation criteria. The average deviation for on-axis was 1.39%.

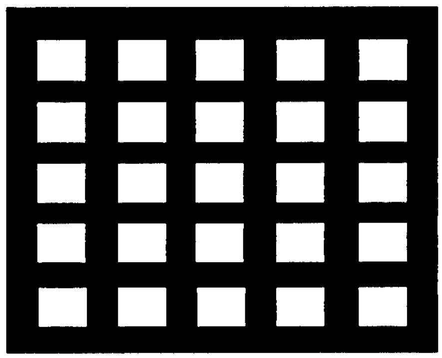
Contrast uniformity

Test Item ID: Honeywell, EL, 24-μm, Number 42.

Objective: To determine variation in contrast uniformity over a large area of the display.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 20-minute circular aperture.

Display pattern: The pattern consisted of 25 windows, each 80 horizontal by 64 vertical pixels. Each rectangular block of pixels was set to a maximum gray level of 63. The background was set to a gray level of 0.



Procedure: Luminance measurements were taken at each of the 25 windows and at locations to the right of each window and beneath each window. For the measurements to the right, the photometer measured a dark area 80 pixels away from the center of the window. For the measurements below each window, the photometer measured an area 64 pixels directly below the center of each window.

Results: Measured luminance readings for each position are given in Table 5, using the following key:

Target	Side
Below	N/A

Key to table

Table 5.
EL luminance measurements for contrast uniformity.

Windows	Column 1	Side	Column 2	Side	Column 3	Side	Column 4	Side	Column 5	Side
Row 1	611.57	3.03	605.40	3.54	593.04	3.64	586.86	3.44	572.45	2.76
Below	3.97		5.15		5.31		7.60		9.12	
Row 2	615.69	4.08	605.40	4.74	597.16	4.69	590.98	4.59	574.51	3.48
Below	7.97		6.32		6.12		11.00		5.23	
Row 3	619.81	4.34	609.51	4.86	590.98	4.94	590.98	4.82	576.57	3.60
Below	5.04		6.14		6.28		6.20		5.46	
Row 4	621.87	4.28	609.51	4.76	603.34	4.86	597.16	4.72	576.57	3.60
Below	5.04		5.81		5.99		5.85		5.72	
Row 5	621.87	3.56	617.75	3.97	605.40	3.99	590.98	4.78	580.69	3.97
Below	3.99		4.72		4.78		4.67		4.90	

Calculated contrast values (L_{max}/L_{min}) based on the lateral and vertical positions relative to each window are provided in Tables 6 and 7, respectively.

Table 6.
EL lateral contrast values.

202.04	170.93	162.71	170.66	207.46
151.01	127.83	127.19	128.70	165.09
142.65	125.42	119.58	122.65	160.00
145.19	128.14	124.15	126.64	160.00
174.57	155.44	151.55	123.71	146.11

Table 7.
EL vertical contrast values.

153.89	117.60	111.63	77.24	62.75
77.26	95.77	97.64	53.75	109.84
122.86	99.33	94.10	95.35	105.66
123.27	104.96	100.69	102.11	100.72
155.67	131.00	126.72	126.43	118.49

Note: Tables 6 and 7 contrast values are based on the floating decimal luminance values (not the two significant digit data in Table 5.

Percent deviation from the average is presented in Tables 8 and 9.

Table 8.
EL lateral percent deviation from the average.

35.80%	14.89%	9.37%	14.71%	39.45%
1.50%	-14.08%	-14.51%	-13.50%	10.96%
-4.12%	-15.70%	-19.62%	-17.56%	7.54%
-2.41%	-13.87%	-16.55%	-14.88%	7.54%
17.33%	4.48%	1.86%	-16.85%	-1.79%

Table 9.
EL vertical percent deviation from the average.

44.37%	10.33%	4.73%	-27.54%	-41.13%
-27.51%	-10.15%	-8.39%	-49.58%	3.05%
15.26%	-6.81%	-11.72%	-10.55%	-0.87%
15.65%	-1.52%	-5.54%	-4.20%	-5.51%
46.05%	22.91%	18.89%	18.62%	11.16%

Discussion: The luminance uniformity is acceptable and appears to be within the allowable ±20% variation from the mean specification. We calculated contrast uniformity using the measured luminance levels in adjacent areas. The calculated contrast ratios were fairly uniform with only two or three of the points showing a variation beyond the ±20% range.
The average lateral deviation was 13.2%. The average vertical deviation was 16.9%.

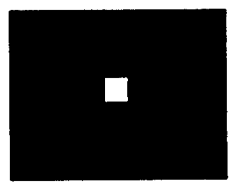
Gamma (luminance response function)

Test item ID: Honeywell, EL, 24-μm, Number 42.

Objective: To determine the luminance response function of the display.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 1-degree circular aperture.

Display pattern: A 40 by 40 pixel square was centrally located and set consecutively to a range of gray levels from 0 to 63. All other pixels were set to zero.



Procedure: The plane of the display was aligned with the photometer focal plane. The 40-pixel square target was centered with the center of the viewing photometer aperture. We measured calibrated luminance in footlamberts. Luminance readings were made for each of the 64 gray levels.

Results: The Gamma curve is shown in Figure 9. The curve displays a shape that may reflect a gray level bit map error. The error appears every 16 gray level increments. Other data that we collected also reflect this type of error.

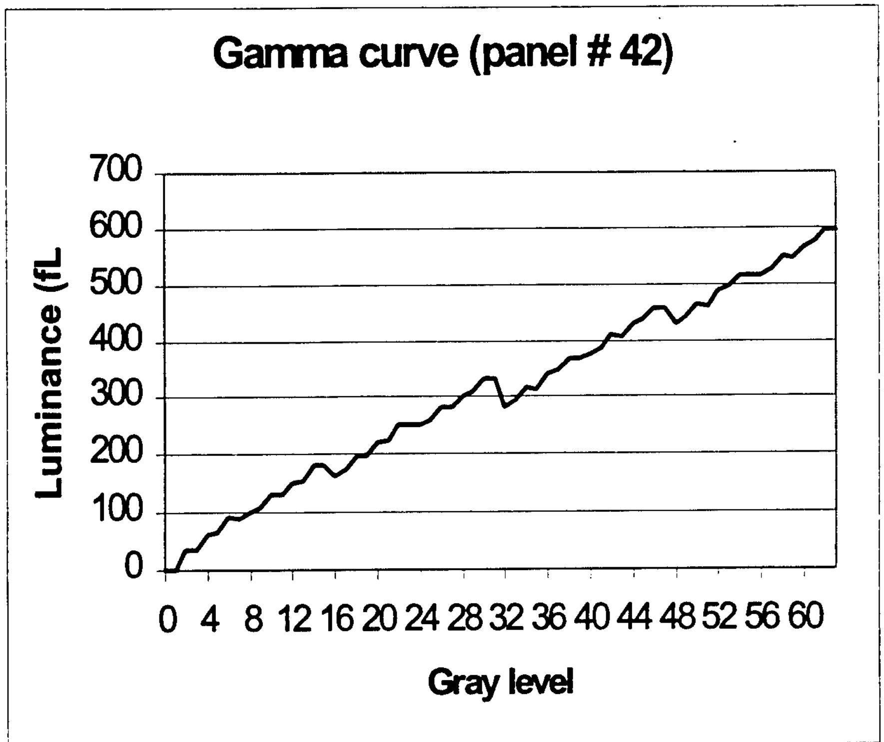


Figure 9. The luminance response curve (Gamma curve) measured for the EL panel.

Discussion: The luminance response shows a linear increase in luminance with a gray level increase, with the exception of the possible bit map error mentioned above.

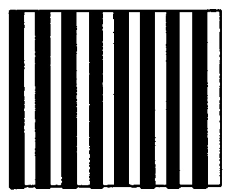
Contrast Transfer Function (CTF)

Test Item ID: Honeywell, EL, 24-μm, Number 42.

Objective: To determine the Michaelson contrast $[(L_{max} - L_{min})/(L_{max} + L_{min})]$ for a series of grid patterns or square wave gratings.

Equipment: A Pritchard 1980A photometer with MS10X and 25X lens with a slit aperture.

Display pattern: A grid pattern with contrast of 0 for the valleys and 63 for the peaks was used. Spatial frequencies ranged from 20 cycles per display width (32 pixel rows on and 32 pixel rows off) up to a high spatial frequency of 640 cycles per display width (1 pixel row on and 1 pixel row off).



Procedure: The slit aperture was aligned near the middle of the display and in the center of the lighted half of the frequency pair and the luminance was recorded. This step was repeated for the darkened half of the frequency pair. This procedure was repeated for each spatial frequency (20, 40, 80, 160, 320, and 640 cycles per display width). Testing was performed with the 10X and the 25X lenses.

Results: Data collected from the two lenses are shown in Tables 10 and 11. The Michaelson contrast data also are plotted in Figure 10. Michaelson contrast is defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$.

Table 10.
CTF data collected with the 10X lens.

Spa. Freq	Light	Dark	Contrast
20	595.00	20.14	0.93
40	613.30	25.63	0.92
80	585.84	34.78	0.89
160	558.38	40.28	0.87
320	530.92	82.38	0.73
640	426.57	103.07	0.61

Table 11.
CTF data collected with a 25X lens.

Spa. Freq	Light	Dark	Contrast
20	530.31	31.71	0.89
40	466.34	36.11	0.86
80	474.87	39.81	0.85
160	472.02	51.75	0.80
320	445.01	87.15	0.67
640	399.51	114.59	0.55

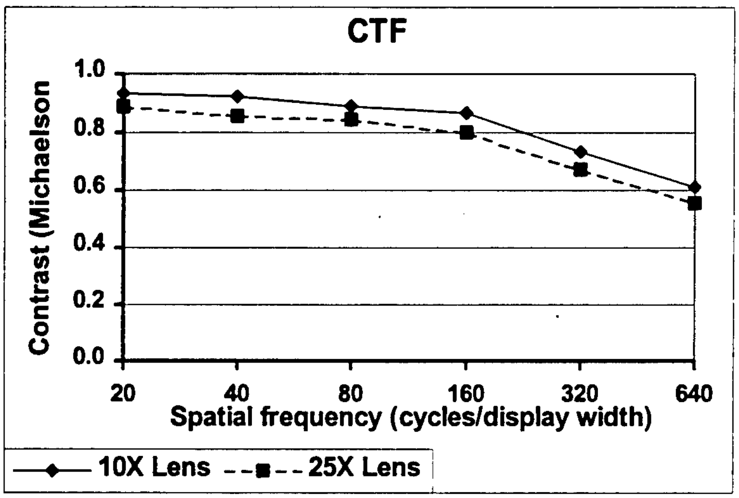


Figure 10. The CTF measured for the EL panel. The two curves were essentially identical but displaced along the Y- axis. For unexplainable reasons, the 10X curve was higher than the 25X curve, which is opposite to expectations. Since the 25X curve has a smaller aperture, the convolution product of the narrower slit aperture with the grid pattern should have yielded slightly higher values than the 10X lens yielded.

Discussion: The contrast transfer function was good. At the Nyquist frequency, the contrast was about 60%, which is reasonable for this display.

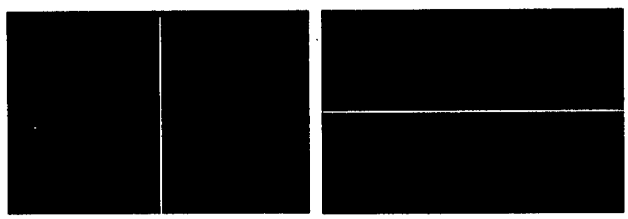
Modulation transfer function (MTF)

Test sample ID: Honeywell, EL, 24-μm, Number 42.

Objective: To determine the horizontal and vertical MTF for the display.

Equipment: A Pritchard 1980A photometer with the 25X lens with a slit aperture. The display was mounted on an Oriel (model #16338) precision horizontal translator.

Display pattern: A single pixel column or row was turned on while all remaining pixels were turned off.



Vertical pattern Horizontal pattern

Procedure: Aligned the slit aperture over the middle of the lighted pixel column. Assured that the orientation of the slit exactly coincided with the pixel column by translating the stage along the vertical axis and visually confirming that the slit remained in the middle of the pixel column. The slit was returned to the center of the display column and then moved horizontally 128 μm. The line was then scanned in 1 μm increments for a total of 256 points which allows a power of 2 fast Fourier transform (FFT) to be performed on the array. This process was then repeated for the horizontal pattern.

Results: The vertical and horizontal MTFs are shown in Figure 11. The two curves essentially were identical which was expected given the horizontal and vertical pixel pitch and fill factor dimensions were the same. The MTF fell to about 40% of the maximum at the Nyquist frequency ($\approx$21 cycles/mm).

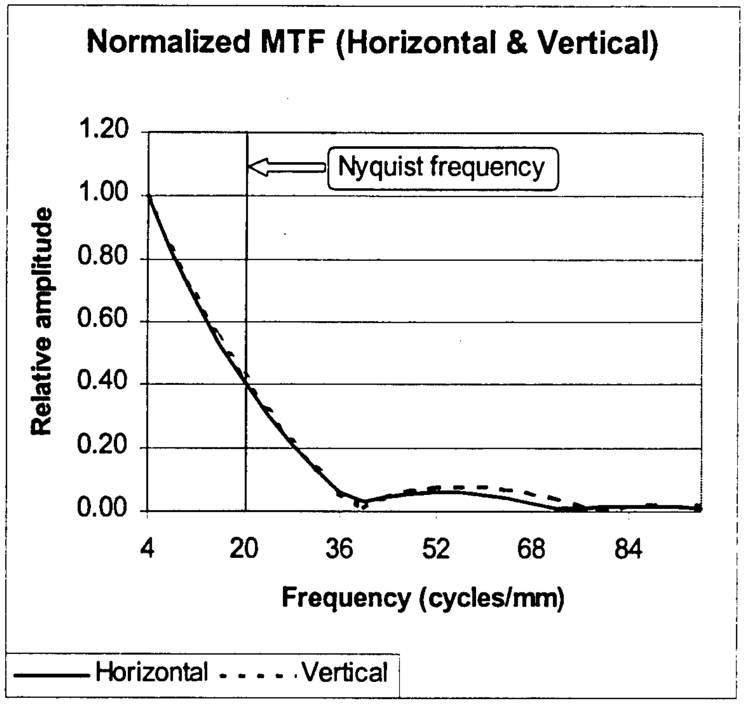


Figure 11. MTF curves measured for the vertical and horizontal linespread curves.

Discussion: Given the large effective fill factor (see below), the MTFs were as expected and showed a drop off to 40% of peak at the Nyquist frequency.

Spectral characteristics

Source Sample: Honeywell, EL, 24-μm, Number 42.

Objective: To determine the spectral distribution and chromaticity of the display's emitted light.

Equipment: A Photo Research PR704 Spectrascan and a portable lap top computer.

Display pattern: A 100 by 100 pixel window was centrally located and set to a gray level of 63. All other pixels set equal to 0.

Procedures: Scan the display and measure the spectral distribution of the display and determine the chromaticity of the emitted light.

Results: 1931 CIE chromaticity: x = 0.5212 y = 0.4760 (Figure 12).

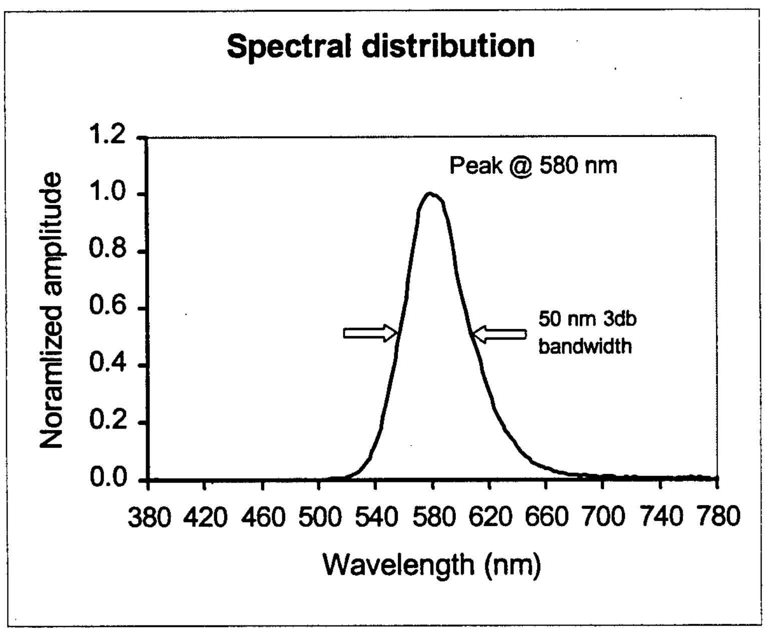


Figure 12. Spectral distribution of the EL display (50nm 3db bandwidth).

Discussion: The spectral distribution of the emitted light was a relatively narrow band (50nm 3db bandwidth) with a peak at 580 nm.

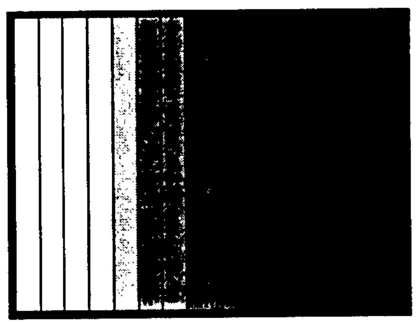
Perceptible gray levels

Test item ID: Honeywell, EL, 24-μm, Number 42.

Objective: To determine the number of perceptible gray levels.

Equipment: Human observers and a Pritchard 1980A photometer.

Display pattern: A 16 panel gray level pattern (80 pixel/column), programmed by Honeywell engineers to provide for a square root of 2 increment in luminance per panel, was used.



Gray level pattern

Procedure: Observers viewed the display and counted the number of gray levels that appeared separate and distinct from all other gray levels. The observers were instructed not to count each bar where a border was observed but rather to judge the number of separable gray levels.

Following the observations, we measured the luminance of each of the bars and plotted the luminance along with a line of slope equal to minus square root of 2 (Figure 13).

Results: The six observers had scattered estimates of the number of gray levels. See Table 12.

Table 12.
Perceptible gray level measurements.

Observer	Gray levels
VA	7
HB	7
SM	12
TH	9
VK	10
BM	5
Average	8.3

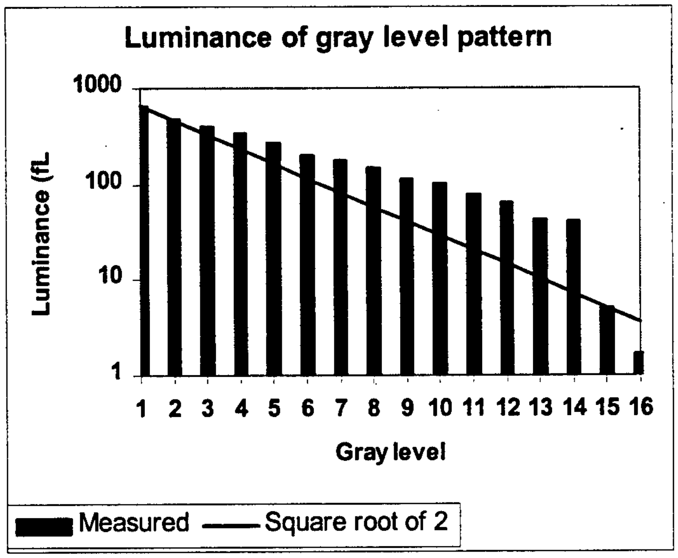


Figure 13. Luminance of the 16 gray levels (bars) used in the perception of gray level test. The straight line represents a negative square root of two line. The square root of two is used for approximating the constant luminance increment threshold of the eye.

Discussion: The average number of grey levels observed was 8.3. The range was from a minimum of 5 to a maximum of 12. This is a very subjective test; however, its consequences are very important.

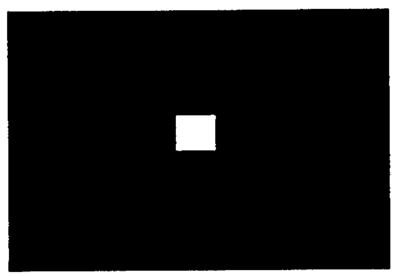
Temporal Response

Test item ID: Honeywell, EL, 24-μm, Number 40.
Note: USAARL did not measure the temporal response, but rather witnessed this measurement at Honeywell, Inc.

Objective: To determine if the modulation of the presented image is degraded with increasing temporal frequency.

Equipment: A Team Systems, Inc. video generator; Tektronix, Inc. digital oscilloscope.

Display pattern: A 100 by 100 pixel square was centrally located and set to maximum luminance. All other pixels were set to zero.



Procedure: The temporal output of the video generator was set to a low frequency value of 1 Hertz (Hz), and the modulation of the output display was measured. Then, the video generator output was changed to 30 Hz, and the resulting modulation was measured and compared to that obtained for the 1 Hz signal.

Results: There was no significant reduction in the modulation when the display pattern was switched from 1 Hz to 30 Hz.

Discussion: Because the display's Nyquist frequency is 30 Hz, the results of this measurement imply that no significant loss in modulation occurs over the display's temporal bandwidth.

Predicted MTF

Test item ID: Honeywell, EL, 24-μm, Number 42.

Objective: Verify the measured MTF by comparing it with the predicted MTF of the display.

Equipment: Computer

Procedure: The MTF can be calculated using a sinc function (Barten, 1991, 1993; Infante, 1993) of the following form.

$$MTF(\mu) = \left| \sin(\Pi\sqrt{F_f}X_p\mu) / (\Pi\sqrt{F_f}X_p\mu) \right| = \left| \sin(\Pi X_a\mu) / (\Pi X_a\mu) \right|$$

where μ is spatial frequency, F_f is the fill factor and X_p is the pixel pitch.

We measured the predicted MTF for the Honeywell 24-µm display in order to verify the MTF measurements made photometrically. According to design engineers, the display had a fill factor of about 0.84. Our measurements of fill factor were considerably higher owing to the pixel light scatter due to the Lambertian surface. The linespread function measured to calculate the MTF had a half height width of 28µm. Using the square of this half height measurement as an indicator of the active area and given the pixel pitch of 24.1µm provides for a fill factor of 1.35. Using the above equation to simulate the MTF, the predicted MTF is shown in Figure 14. At the Nyquist frequency of 20.83 cycles/mm, the predicted MTF had fallen to 41. The measured MTF had a value of 41% of peak at 20 cycles/mm. The fill factor used to predict the MTF was greater than the actual square of the pixel pitch. The concept of an "effective fill factor" is to find the predicted MTF curve that closely matches the measured MTF curve by adjusting the fill factor value in the predicted MTF formulation. By way of comparison, the fill factor of 0.84 provided by the design engineers would have had a value of 73.6% of peak at the Nyquist frequency. Clearly the display's MTF is not close to this measurement.

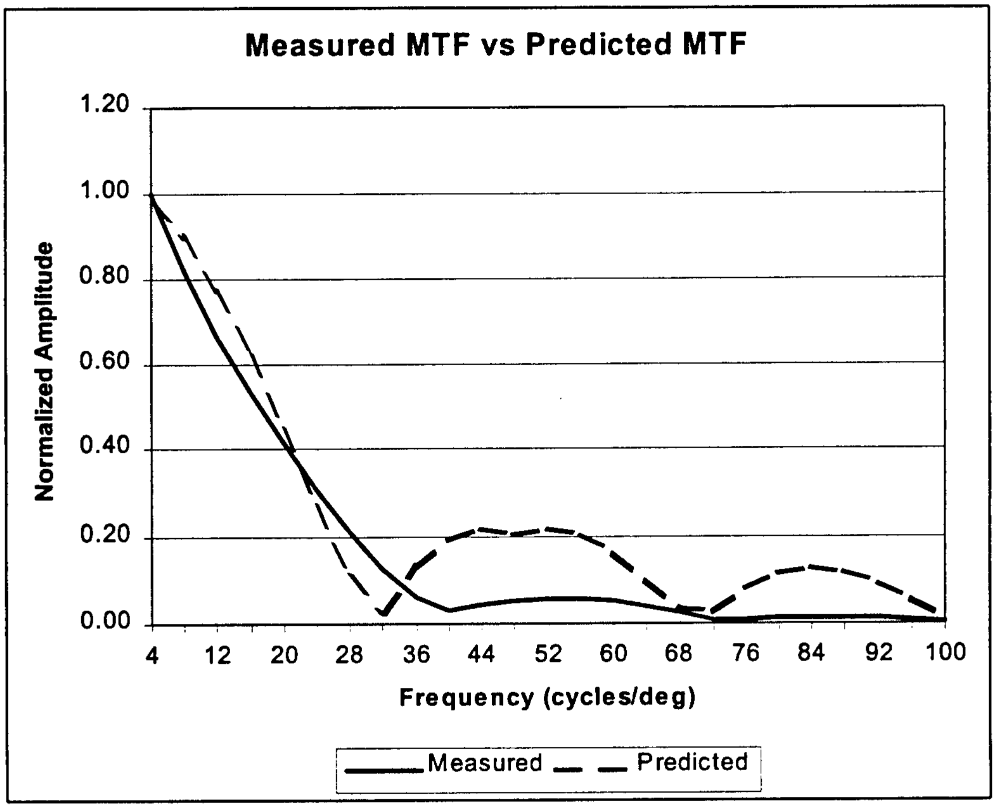


Figure 14. Measured MTF versus the predicted MTF based upon a fill factor of 1.35.

Kaiser Electronics, Inc. LCD tests

The first LCD source (#1) experienced a failure early in our testing sequence and therefore most of data presented here were collected on Kaiser's source #9. Kaiser Electronics, Inc., provided the required sources, backlight with fiber optic bundle, and interface electronics for the evaluation. All testing was performed at USAARL. Some tests were observed by a Kaiser, Inc. engineer.

Pixel geometry

Test Item ID: Kaiser 12-μm LCD display, Number 9.

Objective: To document pixel geometry and pixel pitch.

Equipment: A Zeiss, Inc. light microscope with a 16X and 50X objective lens, equipped with a video camera (COHU Model # 768X493 CCD); a laboratory computer with a video capture card; and Adobe Photoshop software.

Procedure: The image source was placed on an XY-translator stage beneath a microscope objective. The panel was lighted from above via the microscope's light source. Using a 16X and 50X objective lens, a small patch of pixels was imaged by the CCD camera and digitally captured by computer, and the image was saved as a graphics file. Using Adobe Photoshop, the image was analyzed, and measurements of pixel geometry were made using a mensural technique. Calibration was calculated using a previously stored image of a 1/100 mm microscope stage.

Results: Figure 15 is a photomicrograph of a pixel patch of the LCD source of about 8 by 6 pixels. The photomicrograph provides details of the microscopic structure not commonly seen under normal viewing conditions. Figure 16 shows an enlarged section of the pixel patch shown in Figure 15. We measured pixel pitch to be 11.85 µm. The pixel fill factor was determined to be 0.38 based upon an active pixel area of 6.05µm wide and 8.75µm tall. Kopin engineers reported that the fill factor value was 0.32. The fill factor was difficult to measure owing to insufficient light at the high magnification used in our measurements. To overcome this deficiency, we digitally enhanced a patch of on-pixels as shown in Figure 17. The on-pixel area corresponds to the active pixel area illustrated in Figure 16.

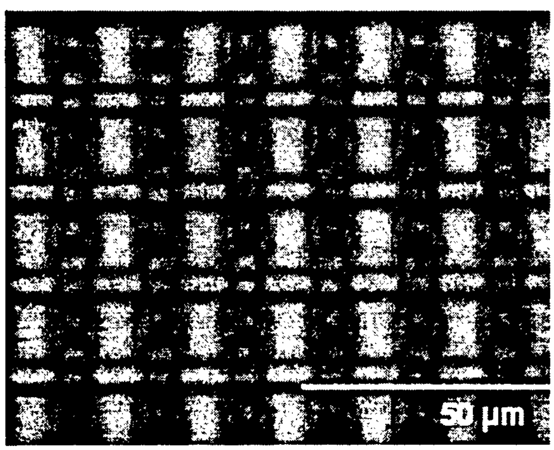


Figure 15. Photomicrograph of 12-μm LCD showing a pixel patch of about 8 by 6 pixels. Illumination is artificial and is from directly above.

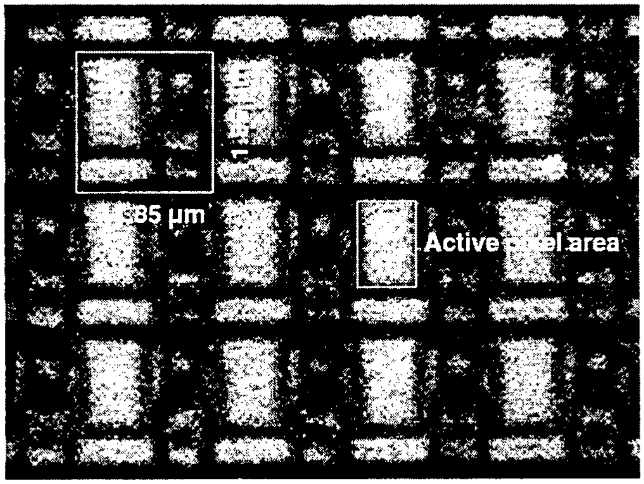


Figure 16. Enlarged subsection of Figure 15. Note the active pixel area is the white rectangle. Illumination is artificial, and the square area, designated as a single pixel, may or may not be co-located with the actual pixel area, although the square is the size of the actual pixel area.

Discussion: Our measurements likely have an accuracy within ± 0.2 μm. As can be seen in Figure 17, the edge of the pixel is blurred and therefore made measurements of fill factor less accurate. The low fill factor leads to an improved MTF and CTF.

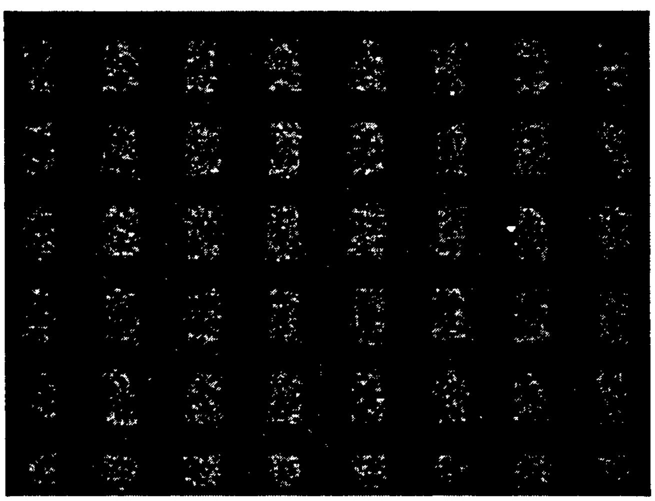


Figure 17. Digitally enhanced image of back-lit on-pixels. The real image was too dim to illustrate due to the high magnification. The color of the pixels was altered as a result of the enhancement.

Pixel defects

Source Sample: Kaiser 12-μm LCD displays, Numbers 1 and 9.

Objective: To document display and pixel defects.

Equipment: A Zeiss, Inc. light microscope with a 16X and 50X objective lens, equipped with a video camera (COHU Model # 768X493 CCD); a laboratory computer with a video capture card; and adobe Photoshop software.

Results: Due to the physical configuration of the display and drive electronics, we were unable to use photomicroscopy to document pixel defects. However, while viewing the source under 10X and 25X photometric magnification, several pixels were noted to be continuously "on." Display # 1, which showed signs of pixel clearing, was unfortunately destroyed prior to any conclusive evaluation.

Discussion: While no major pixel defects were noted, it is our opinion that the number of stuck-on pixels is greater than that normally observed in panel size LCDs.

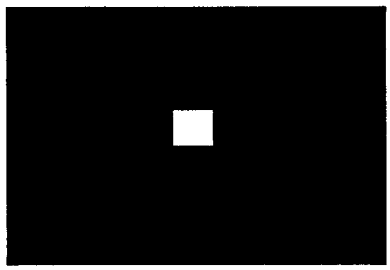
Maximum luminance

Source Sample: Kaiser 12-μm LCD display, Number 1.

Objective: To determine the maximum luminance.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 1-degree circular aperture.

Display pattern: A 100 by 100 pixel square was centrally located and set to maximum luminance (digital level = 63). All other pixels were set to zero.



Display Pattern.

Procedure: The plane of the display was aligned with the photometer focal plane. The 100 pixel square target was centered with the center of the viewing photometer aperture. The calibrated luminance was measures in footlamberts. To investigate maximum contrast for this condition, luminance measurements were taken at points 100 pixels to the right and below the center of the 100 pixel square target.

Results: The LCD was backlit by a Kaiser provided arc lamp brought to the display by a fiber optic bundle which provided a moderately spatially-uniform backlight (see luminance uniformity below).

The maximum luminance measured was 167 fL for source # 1. Contrast ratio values are given in Table 13. Using a 25 square pattern, source # 9 achieved a 236 fL peak luminance in the middle of the display.

Table 13.
LCD luminance and contrast values.

	Luminance	Contrast ratios
Target	167 fL	
Side	5.66 fL	29.5
Below	5.89 fL	28.4

The contrast ratio equals the maximum target luminance divided by the minimum or background luminance.

Discussion: The peak luminance is in some ways meaningless since it entirely depends on the luminance of the backlight. Determining the luminance of the backlight required to achieve a system luminance output to meet design goals requires knowledge of the HMD optical design. Lacking this knowledge, we made a comparison between the HIDSS CRT based system with the present source to understand the backlight requirements. The HIDSS CRT produced a peak luminance of 3300 fL. Using a transmittance figure of about 6 percent for this LCD (Figure 18), a backlight needs to produce a luminance of 55,000 fL.

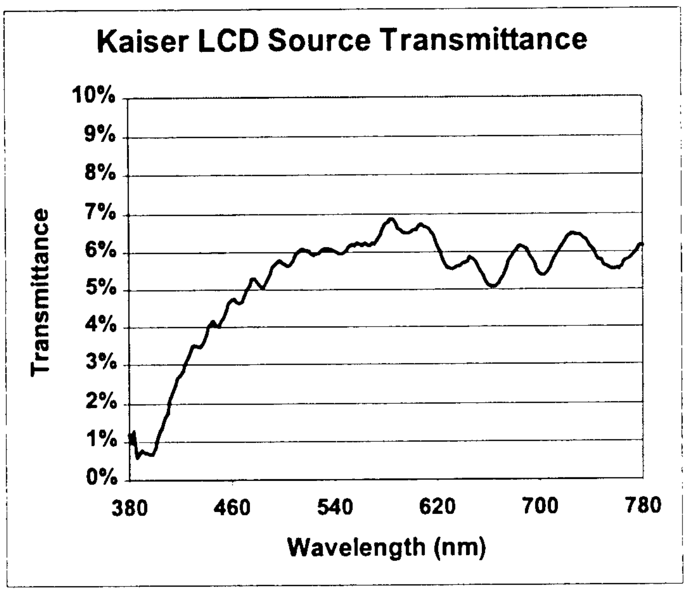


Figure 18. Transmittance for Kaiser's LCD.

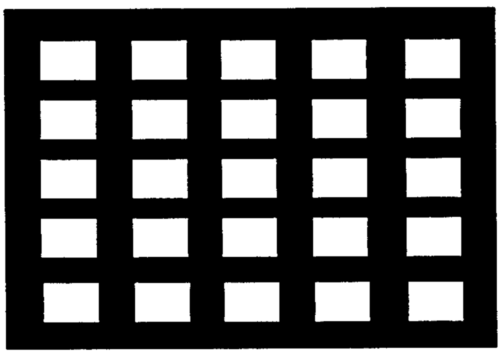
Luminance uniformity

Source Sample: Kaiser 12-μm LCD display, Number 9.

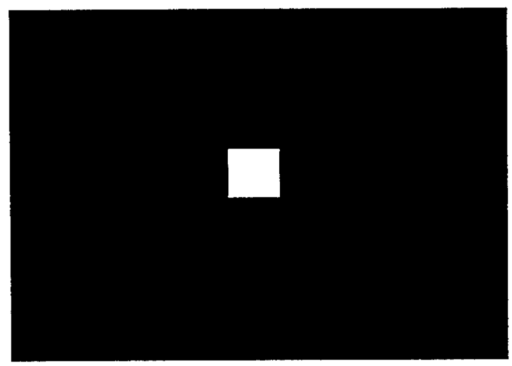
Objective: To determine variation in luminance for both on-axis and off-axis orientations.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 20-minute circular aperture.

Display pattern: For on-axis uniformity, a 25 window pattern was used with each window being 80 horizontal by 64 vertical pixels in size. Each rectangular block of pixels was set to a maximum gray level of 255. The background was set to a gray level of 0. For off-axis uniformity, a 100 by 100 pixel square in the middle of the display was set to 255, while all remaining pixels were set to off.



Display pattern for on-axis luminance uniformity.



Display pattern for off-axis luminance uniformity.

Procedure: On-axis - Luminance measurements were taken for each of the 25 windows. Off-axis - Luminance measurements were taken for only the center window at each of several horizontal and vertical angles.

Results: The on-axis luminance values for the 25 window pattern are presented in Table 14. Table 15 shows the deviations from the mean for the data shown in Table 14.

Table 14 shows the on-axis luminance in footlamberts for each of the 25 rectangles.

<u>Table 14</u>.
LCD on-axis luminance (fL).

193	210	222	240	230
220	225	235	246	245
218	224	236	247	245
222	233	237	249	240
230	235	237	250	240

Table 15 shows on-axis percent deviation from the average luminance.

Table 15.
LCD on-axis percent deviation from the average luminance.

-16.80%	-9.46%	-4.57%	3.39%	-0.90%
-5.18%	-3.34%	0.94%	5.83%	5.22%
-6.40%	-3.59%	1.55%	6.45%	5.22%
-4.57%	0.33%	2.16%	7.06%	3.39%
-0.90%	0.94%	2.16%	7.67%	3.39%

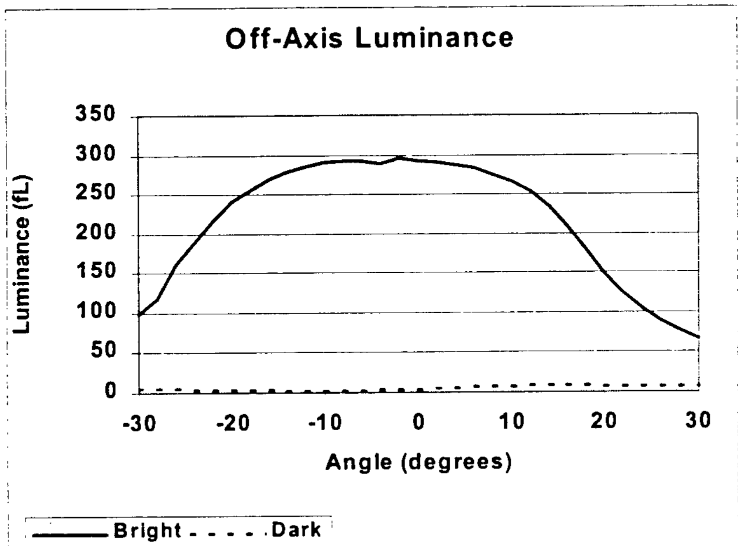


Figure 19. Off-axis luminance as a function of angular orientation. Luminance is reportedly higher here owing to the numerical aperture of the standard lens and measurement distance used to collect these data, as opposed to higher magnification lenses used to collect the other data reported here at short working distances. The lens used here was selected in order to collect data with a smaller angle of regard.

Discussion: As shown in Table 15, the on-axis luminance did not deviate from the mean by more than ±20%. Although the luminance uniformity meets Comanche requirements, it should be remembered that the uniformity is largely the result of the backlight and this backlight is not intended for final use in the HIDSS. For off-axis luminance, luminance falls off with angular distance, as expected for a LCD (Figure 19).

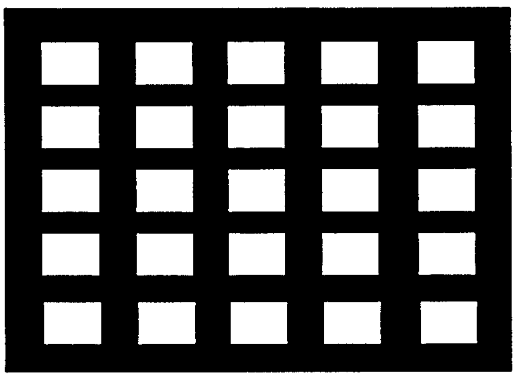
Contrast uniformity

Test Item ID: Kaiser 12-μm LCD display, Number 9.

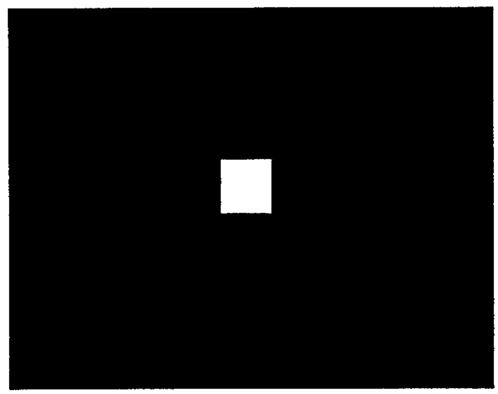
Objective: To determine variation in contrast uniformity over a large area of the display.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 20-minute circular aperture.

Display pattern: For on-axis contrast, the 25 window pattern (discussed above) was used. For off-axis contrast, the single 100 pixel square window in the middle of the display was used.



Display pattern for on-axis luminance uniformity.



Display pattern for off-axis luminance uniformity.

Procedure: Relative luminance measurements were taken for each of the 25 windows and at locations to the right of each window and beneath each window. For the measurements to the right, the photometer measured a dark area 80 pixels away from the center of the window. For the measurements below each window, the photometer measured an area 64 pixels directly below the center of each window.

Results: Measured relative luminance readings for each position are given in Table 16, using the following key:

Table 16 Key

Target	Side
Below	N/A

Table 16.
Relative LCD luminance measurements for contrast uniformity.

1.360	0.051	1.480	0.054	1.560	0.056	1.690	0.059	1.620	0.045
0.056		0.055		0.058		0.061		0.054	
1.550	0.058	1.580	0.060	1.650	0.063	1.730	0.064	1.720	0.042
0.061		0.059		0.061		0.064		0.054	
1.530	0.065	1.576	0.064	1.660	0.068	1.740	0.069	1.720	0.048
0.074		0.074		0.072		0.071		0.058	
1.560	0.068	1.640	0.070	1.670	0.078	1.750	0.078	1.690	0.045
0.072		0.082		0.069		0.070		0.059	
1.620	0.060	1.650	0.070	1.670	0.057	1.760	0.055	1.690	0.039
0.051		0.057		0.057		0.059		0.055	

Lateral and vertical contrast ratios calculated from the data shown in Table 16 are provided in Tables 17 and 18, respectively.

Table 17.
Lateral contrast ratios.

26.67	27.41	27.86	28.64	36.00
26.72	26.33	26.19	27.03	40.95
23.54	24.63	24.41	25.22	35.83
22.94	23.43	21.41	22.44	37.56
27.00	23.57	29.30	32.00	43.33

Table 18.
Vertical contrast ratios.

24.29	26.91	26.90	27.70	30.00
25.41	26.78	27.05	27.03	31.85
20.68	21.30	23.06	24.51	29.66
21.67	20.00	24.20	25.00	28.64
31.76	28.95	29.30	29.83	30.73

Since we measured off-axis luminance with the pixels on and then repeated this measurement with the pixels off, we can calculate a large area contrast using the data shown in Table 16. The resulting contrast plot is shown in Figure 20. Note that the resulting curve is somewhat off-center, although this may be an artifact due to the prototype mounting of the source device.

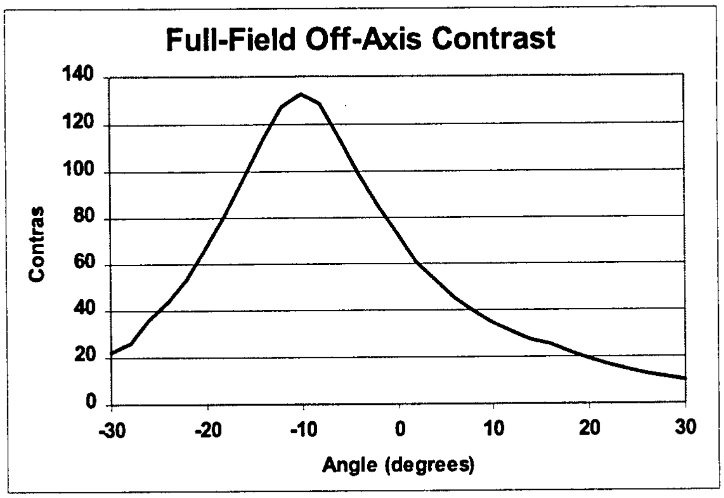


Figure 20. Full-on/full-off off-axis contrast.

Discussion: On-axis luminance and contrast uniformity appear good with the present backlight, but these uniformity figures have no relationship since the final backlight has yet to be determined.

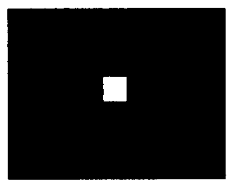
GAMMA (luminance response function)

Test item ID: Kaiser 12-μm LCD, Number 9.

Objective: To determine the luminance response function of the display.

Equipment: A Pritchard 1980A photometer with MS10X lens with a 1-degree circular aperture.

Display pattern: A 40 by 40 pixel square was centrally located and set to a range of gray levels from 0 to 255. All other pixels were set to zero.



Procedure: The plane of the display was aligned with the photometer focal plane. We centered the 40-pixel square target with the center of the viewing photometer aperture. We measured calibrated luminance in footlamberts. Luminance readings were made for each of the 256 gray levels.

Results: As can be seen in Figure 21, the Gamma was essentially monotonic up to a gray level of about 160. From a gray level of 160 on, the curve saturates and then rescinds. If this drop-off was due to a bit map problem, we would expect to see a break in the curve and a portion of the monotonic curve repeated.

Discussion: The Gamma curve shown in Figure 21 is a bit confusing since we cannot construct a hypothesis for this kind of response curve. Up to a gray level of 64, the curve is very shallow and shows only modest increases in luminance for each gray level step. From a gray level of 64 to 160 , the curve is steep and monotonic. As noted above, from 160 on, the curve saturates and then rescinds. This is not typical of the LCDs we have measured, and we don't think that it is a technology issue, but rather a manufacturing issue or foundry problem.

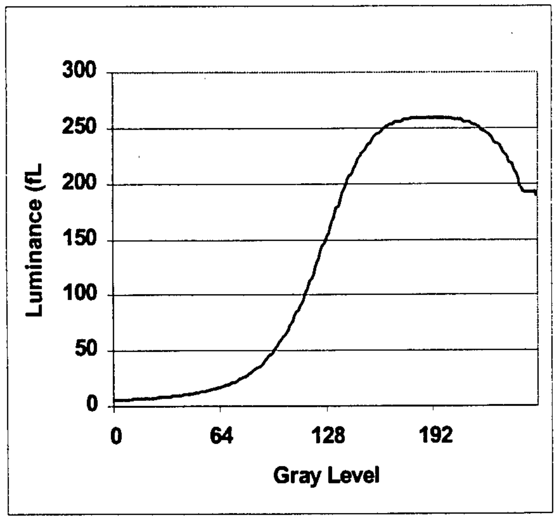


Figure 21. Luminance response curve (Gamma curve) for the Kaiser LCD. Luminance readings were made for each of the 0 to 255 gray levels.

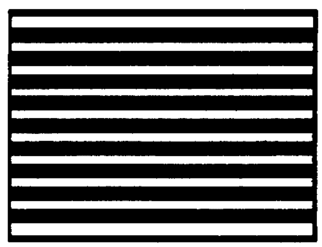
Contrast Transfer Function (CTF)

Test Item ID: Kaiser 12-μm LCD, Number 9.

Objective: To determine the Michaelson contrast $[(L_{max}-L_{min})/(L_{max}+L_{min})]$ for a series of grid patterns or square wave gratings.

Equipment: A Pritchard 1980A photometer with MS25X lens with a slit aperture.

Display pattern: A horizontal grid pattern with contrast of 0 for the valleys and 255 for the peaks was used. Spatial frequencies ranged from 20 cycles per display width (32 pixel rows on and 32 pixel rows off) up to a high spatial frequency of 512 cycles per display width (1 pixel row on and 1 pixel row off).



Procedure: We aligned the slit aperture near the middle of the display and in the center of the lighted half of the frequency pair and recorded the luminance. We then scanned two spatial periods of the grid pattern in 48 evenly spaced steps. We determined the peak and trough of the recorded measurements and calculated Michaelson contrast $[(L_{max}-L_{min})/(L_{max}+L_{min})]$. This procedure was repeated for each spatial frequency (16, 32, 64, 128, 256, 512 cycles per display width).

Results: Figure 22 shows the CTF. The curve is expressed in cycles per millimeter calculated using a nominal pixel pitch of 12μm. The highest frequency tested, the Nyquist frequency of 512 vertical cycles per display width, equals 41.67 cycles/mm. Note, at this frequency, the contrast was 0.85. Only minimal fall-off was observed,

Discussion: The CTF showed only minimal fall-off, probably owing to the displays low fill-factor. For a discussion of the fill factor's effect on the display's spatial frequency response, see the section on the Predicted MTF below.

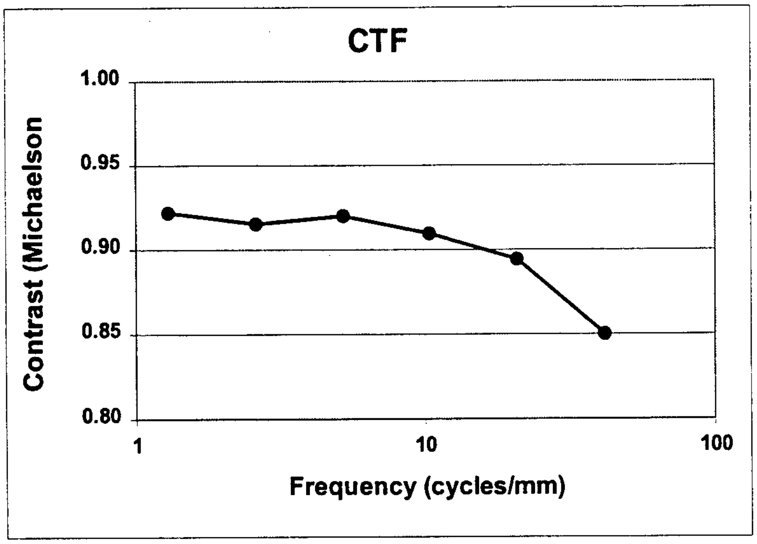


Figure 22. Vertical CTF for the Kaiser LCD.

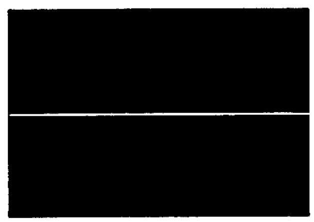
Modulation transfer function (MTF)

Test sample ID: Kaiser LCD, 12-μm, Number 9.

Objective: To determine the horizontal and vertical modulation transfer function (MTF) for the display.

Equipment: A Pritchard 1980A photometer with the 25X lens with a slit aperture. The display was mounted on a Oriel (model #16338) precision horizontal translator.

Display pattern: A single horizontal pixel row was turned on; all remaining pixels were turned off.



Procedure: The horizontal slit aperture was aligned over the middle of the lighted pixel row. We ensured that the orientation of the slit exactly coincided with the pixel row by translating the stage along the horizontal axis and visually confirmed that the slit remained in the middle of the pixel row. The slit was returned to the center of the display and then moved vertically 32 μm. The line then was scanned in 0.5 μm increments for a total of 128 points which allowed a power of 2 FFT to be performed on the array.

Results: The horizontal linespread function (vertical MTF) was measured and is displayed in Figure 23. The width at half height was about 9 μm. A measurement of the vertical linespread (horizontal MTF) was not made due to the difficulty in vertically mounting the display and driver electronics on our precision mount. The vertical linespread should be narrower than the horizontal linespread owing to the narrower gap between active pixel areas (see Figure 17). The vertical MTF is shown in Figure 24. At a Nyquist frequency of 41.67, the curve had a value of 62% of peak.

Discussion: Since the pixel's active area was taller than it was wide, a single MTF can not describe both the vertical and horizontal spatial frequency spectra. Due to logistical problems, we could only measure the vertical MTF. The vertical MTF will be considerably poorer than the horizontal MTF. See a comparison below in the Predicted MTF section.

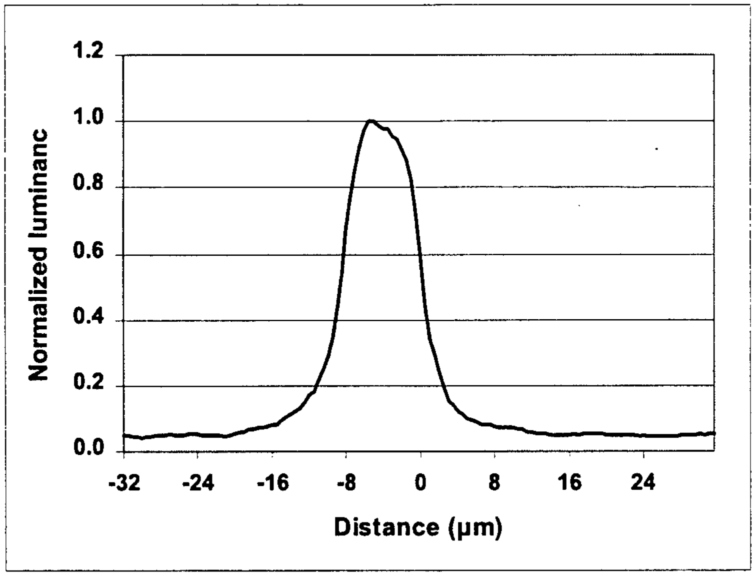


Figure 23. Normalized Kaiser 12-µm horizontal linespread curve.

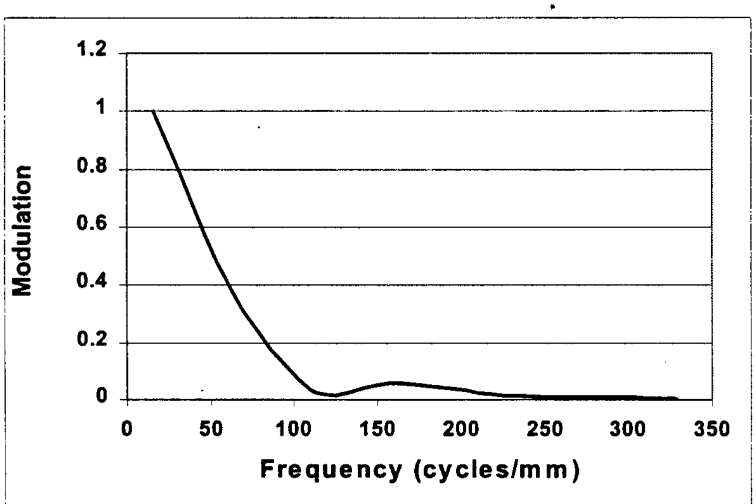


Figure 24. Normalized vertical MTF for the Kaiser 12-µm display.

Spectral charateristics

Source Sample: Kaiser LCD, 12-μm, Number 9.

Objective: To determine the spectral distribution and chromaticity of the display's emitted light.

Equipment: Photo Research PR704 Spectrascan and a portable lap top computer.

Display pattern: A 100 by 100 pixel window was centrally located and set to a gray level of 63. All other pixels set equal to 0.

Procedures: The display was scanned and the spectral distribution of the display was measured to determine the chromaticity of the emitted light.

Results: Based upon the source provided and the characteristics of the display, the spectral output is shown in Figure 25. The curve peaked at 548 to 550 nm with a half height bandwidth of 46 nm.

Discussion: The spectral output of the display is almost entirely due to the backlight and the present backlight is not planned for fielded use.

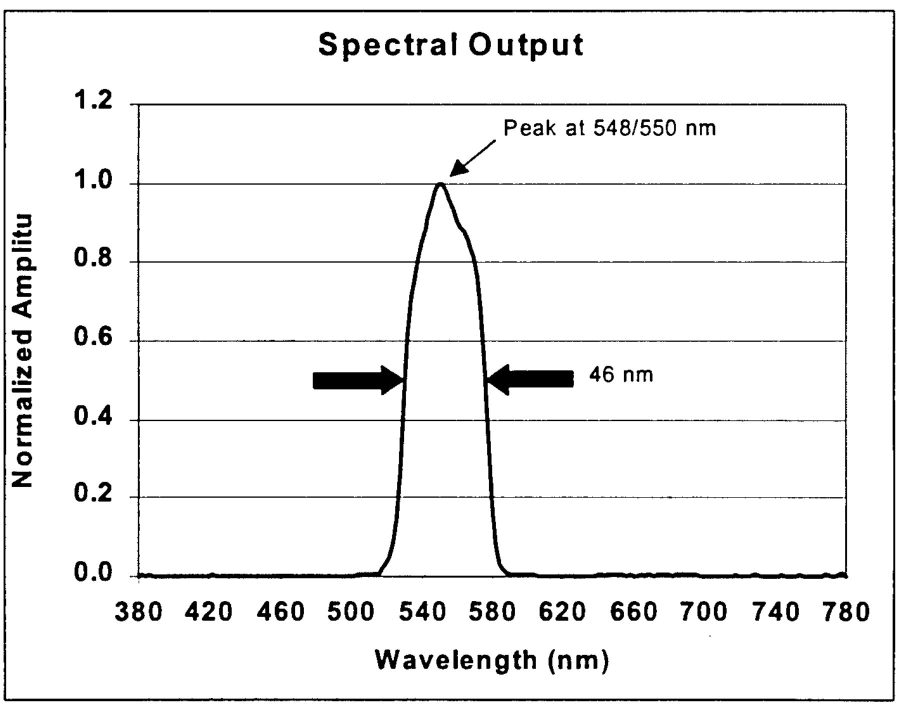


Figure 25. Spectral output of the Kaiser LCD.

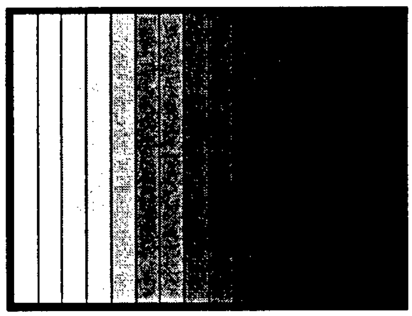
Perceptible gray levels

Test item ID: Kaiser 12-μm LCD, Number 9.

Objective: To determine the number of perceptible gray levels.

Equipment: Human observers and a Pritchard 1980A photometer.

Display pattern: A 16 panel gray level pattern (80 pixel column) was used.



Gray level pattern

Procedure: Observers viewed the display and counted the number of gray levels that appeared separate and distinct from all other gray levels. The observers were instructed not to count each bar where a border was observed but rather to judge the number of separable gray levels.

Results: Six observers made perceptual estimates of the number of distinct gray levels shown on the display. Table 19 provides a summary of the number of gray levels counted by each of the observers. Figure 26 shows the distribution of gray levels along with the predicted fall-off in luminance using a square-root-of-two model.

Table 19.
Perceptual gray levels.

Observer	Gray levels
ER	6
HB	6
SM	10
TH	8
VK	11
M	5
Average	7.7

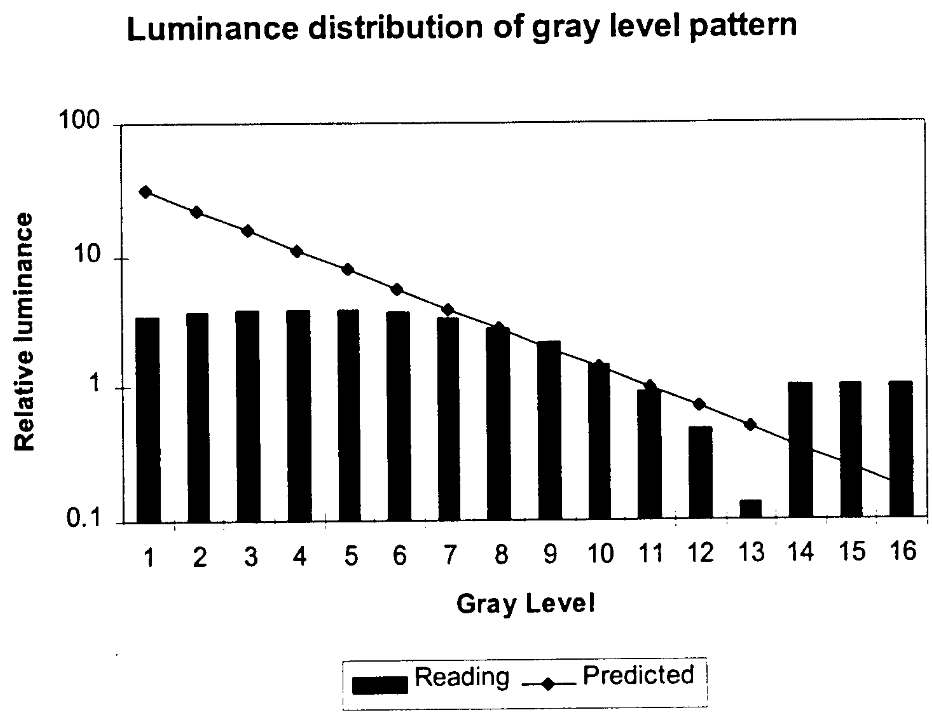


Figure 26. Relative luminance for each of the 16 gray levels. The majority of the gray levels show little distinction. The line is predicted gray level curve based upon user defined gray level inputs corresponding to a square-root-of-two differential.

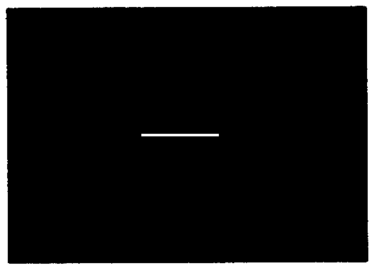
Temporal Response

Test item ID: Kaiser 12-μm LCD, Number 9.

Objective: To determine the rise and fall times of the display.

Equipment: Pritchard 1980A photometer and computer generated image.

Display pattern: A horizontal line of 100 pixels by 4 pixels was turned off and on by way of a computer animation. The temporal frequency was 0.5 Hz.



Results: Table 20 shows the rise and fall times measured for the display. Note that the nominal cut-off frequencies were 67.39 and 40.26 Hz for the 10% to 90% condition and 0% to 100% condition, respectively. The gray levels were 0 and 63 or the full extent of the gray level range.

Table 20.
Rise and fall times for the LCD.

Condition	Rise time	Fall time	Nominal Cut-off frequency
10% to 90%	8.98 msec		67.39 Hz
90% to 10%		5.86 msec	
0% to 100%	15.64 msec		40.26 Hz
100% to 0%		9.2 msec	

Discussion: The rise and fall times are adequate for good temporal perception.

Predicted MTF

Test item ID: Kaiser 12 μm LCD, Number 9.

Objective: Verify the measured MTF by comparing it with the predicted MTF of the display.

Equipment: Computer

Procedure: Using the measured height and width of the active pixel area, imaginary fill factors were calculated in order to approximate a square active pixel area equal to the width squared and one equal to the height squared. An area measurement of fill factor was required for our model.

Model: The MTF can be calculated using a sinc function (Barten, 1991, 1993; Infante, 1993) of the following form

$$MTF(\mu) = \left| \sin(\Pi\sqrt{F_f}X_p\mu) / (\Pi\sqrt{F_f}X_p\mu) \right| = \left| \sin(\Pi X_a\mu) / (\Pi X_a\mu) \right|$$

where μ is spatial frequency, F_f is the fill factor and X_p is the pixel pitch.

Below is a list of the particular measurements for the LCD, along with several calculations.

Active pixel width =	6.05μm
Active pixel height =	8.75μm
Pixel Pitch =	11.85μm
Calculated Horizontal fill factor =	0.26
Calculated Vertical fill factor =	0.55
Overall fill factor =	0.38

The measured MTF should approximate the predicted MTF using a fill factor of 0.55. As can be seen in Figure 27, the respective MTFs do not match. To match the 62% of maximum value at the Nyquist frequency requires a theoretical fill factor of about 1 as compared to the 0.55. One reason for the error in prediction could be due to the small size of the pixel compared to our slit size. We measured our slit width to be 4μm. However, our calculations suggest that the MTF of the slit, given an impulse shape, would have approximately 98% modulation at the display's Nyquist frequency.

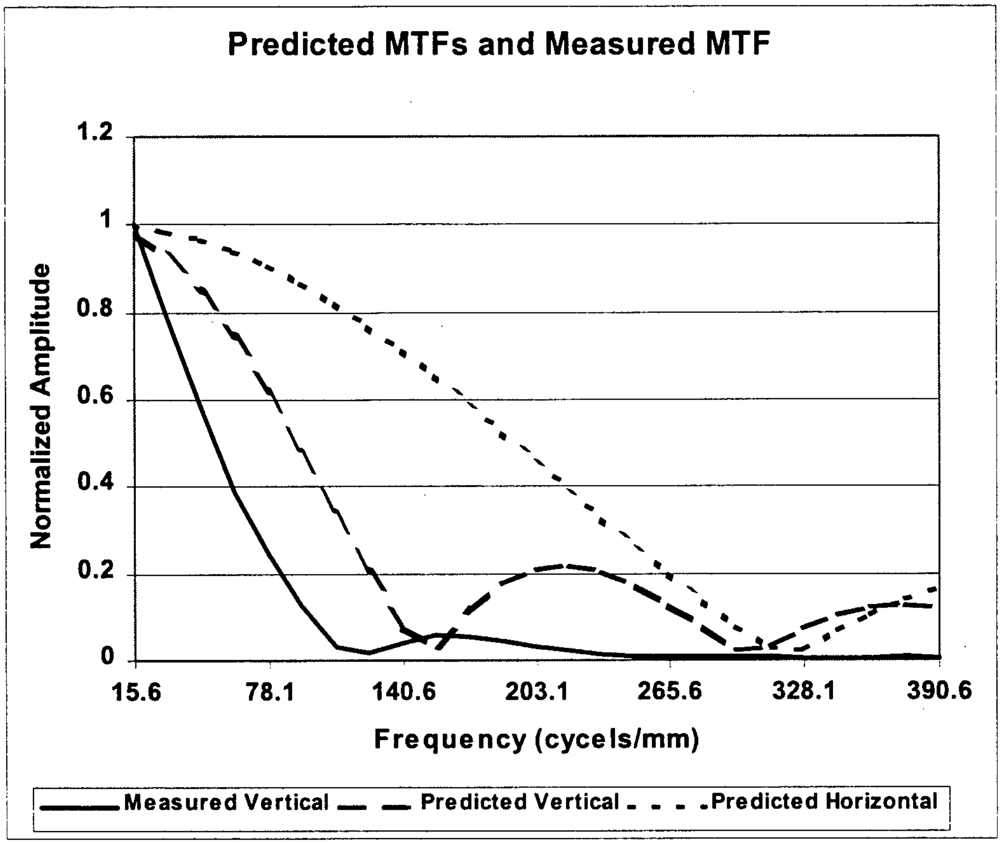


Figure 27. Horizontal and vertical predicted MTFs compared with the measured MTF. The predicted vertical MTF was based upon a fill factor of 0.55 whereas the predicted horizontal MTF was based upon a fill factor of 0.26.

Comparative test summary and discussion

For comparison purposes, test results for both the Honeywell 24-μm EL and Kaiser Electronics 12-μm LCD displays are summarized in Table 21.

The Honeywell 24-μm EL display provided a luminance level of over 600 fL consistently, with excellent contrast ratios of 100 to 200 over most of the display area. This luminance level bodes well for EL technology with expectations of someday soon providing the luminance levels required by Comanche. Luminance uniformity was also excellent and was well within the ±20 percent deviation requirement. The CTF provided adequate contrast out to the Nyquist frequency. The gamma curve showed good linearity, although a probable bit mapping problem existed in the display we tested. This should be repairable with an improved manufacturing technique. Based upon Honeywell testing, the display had a reasonable temporal response.

Only two major shortcoming were noted. First, and the most damaging, the display suffers from "burn-in" of previously displayed imagery. This causes a reduction in contrast and provides for increased noise in the display's imagery. Second, the display had some pixel defects including whole columns of pixels which were steadily on. A sprinkling of single pixels were also steadily on. With the exception of the "burn-in" problem, most defects could be corrected with further advances in manufacturing.

The Kaiser Electronics 12-µm LCD appeared to be a more advanced technology. However, our tests were conducted using a backlight which may or may not reflect future performance using another backlight. First and foremost, a much brighter backlight is required to achieve Comanche specifications. The highest luminance was about 250 fL with contrast ratios of around 30. On-axis luminance uniformity was good but is dependent upon the uniformity of the backlight source. Off-axis uniformity was typical of an LCD with luminance fall off with increasing off-axis angles. No major pixel defects were noted, although clearing was observed in one of the tested displays. The CTF was excellent, which is typical of a display with a low fill factor number. The temporal response was reasonable, although we were unable to perform a detailed analysis of temporal response characteristics.

The major shortcoming of the display was not having a suitable backlight to test. Given the characteristics of the HIDSS, a backlight of around 55,000 fL is required to produce comparative results with the CRT based system. Perhaps this luminance is achievable utilizing a display heater coupled with a high output arc lamp, however the logistics of an arc lamp in a confined cockpit are questionable.

Of the two technologies, the LCD appears to be the most advanced; however, we are concerned by the high luminance requirements of the backlight if it is to achieve operational capability.

Table 21.
Test result comparison.

Test	Honeywell EL	Kaiser LCD
Pixel geometry	24.1μm pixel pitch with a measurable fill factor of 1.35	11.85μm pixel pitch with a fill factor of 0.55
Pixel defects	Major pixel defects were noted including two columns of pixels stuck-on plus other spurious pixels stuck-on. In addition, a burn-in was noted of a previously displayed pattern.	No major pixel defects noted.
Maximum Luminance	Peak of 657 fL	Peak of 260 fL but is backlight dependent.
Luminance uniformity	Luminance uniformity was well within ±20%	Luminance uniformity within ±20%
Contrast uniformity	Contrast ratios were fairly uniform although a few points fell outside the ±20% range.	Contrast ratios were fairly uniform although a few points fell outside the ±20% range.
Maximum contrast	Contrast ratio of 327	Contrast ratio of 29.5
Gamma	Relatively linear curve from 0 to approximately 600 fL. The curve showed signs of bit map errors.	Gamma curve non-monotonic with luminance range of 0 to 260 fL
Contrast transfer function	CTF very good with 60% contrast at the Nyquist frequency (≈21 cycles/mm)	CTF very good with 85% contrast at the Nyquist frequency (≈41 cycles/mm)
Modulation transfer function	See Figure 11	See Figure 24
Spectral characteristics	Peak at 580 nm with a bandwidth of 50 nm	Peak at 548/550 nm with a bandwidth of 46 nm
Perceptible gray levels	Average of 8.3	Average of 7.7
Temporal response	Not measured at USAARL	Nominal cut-off frequency of 67.39 Hz
Predicted MTF	Our prediction of the MTF matched closely the MTF measured for the display.	Our prediction of the MTF did not match the measured MTF.

References

Barten, P.G.H., 1991. Resolution of liquid-crystal displays. *Society of information display digest*, 772-775.

Barten, P.G.H., 1993. Effects of quantization and pixel structure on the image quality of color matrix displays. *Journal of the society of information display*, 1, 147-153.

Gentex, Inc. 1998. Draft Gentex-Government phase IIB design assessment plan, preplanned product improvements for the Aircrew Integrated Helmet System (AIHS) HGU-56P. Carbondale, PA.

Harding, T. H., Beasley, H. H., Martin, J. S., Rash, C. E., McLean, W. E., Mora, J. C., and McEntire, B. J. 1998. Optical and biodynamic evaluation of the Helmet Integrated Display Sight System (HIDSS) for the RAH-66 Comanche Development and Validation Program phase. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 98-22.

Infante, C. 1993. On the modulation transfer function of matrix displays. *Society of information display*, 449-450.

Appendix.

List of manufacturers.

Adobe Systems, Inc.
345 Parl Ave
San Jose, CA 95110

Carl Zeiss, Inc.
One Zeiss Drive
Thornwood, NY 10594

COHU, Inc.
5755 Kearny Villa Road
San Diego, CA 92123

Honeywell, Inc.
2600 Ridgeway Parkway
Minneapolis, MN 55413

Kaiser Electronics
2701 Orchard Park Way
San Jose, CA 95134

Kopin Corporation
695 Myles Standish Blvd.
Taunton, MA 02780

Oriel Corporation
250 Long Beach Blvd.
PO Box 872
Stratford, CT 06497

Planar Systems, Inc.
1400 NW Compton Drive
Beaverton, OR 97006

Team Systems, Inc.
2934 Corvin Dr.
Santa Clara, CA 95051

Tektronix, Inc.
Howard Vollum Park
P.O. Box 1600
Beaverton, OR 97075